Autopilot Sytem Design Of MQ9-Reaper

Shubham Kumar
University of Southern Denmark
shkum20@student.sdu.dk

Abstract– Autopilot is a system that maintains an airplane moving in a specific direction without the need for external assistance. This one's control system is made up of numerous components. The overall goal of the autopilot system is to maintain the aircraft's altitude and direction while also restoring it to its original state if it is displaced. This is done to keep the plane stable laterally, vertically, and longitudinally. Design an autopilot control system for the MQ9-Reaper and perform mission control in this report. Due to the difficulties of this non-linear system control and constructing an autopilot around it, there were challenges.

I. Introduction

From a general standpoint, fixed-wing aircraft need a landing strip to take off and land. A jet engine or a propeller is typically used to provide thrust in this situation. All fixed-wing aircraft have the same wing, rudder, and ailerons. Wright's brother was the first one to invent the fixed-wing. A propeller or jet engine is used to drive a fixed-wing plane forward. The wings are positioned to allow for two-directional airflow. The formation of lift is caused by airflow, which is high at the top of the wing and low at the bottom. [3]. There are some difficulty with fixed wing aircraft. If there's increase in payload then there should be an exponentially increase the wingspan of plane to generate lift.

Fixed-wing aircraft components. Wings are critical because they generate lift against gravity, allowing the plane to take off. It's also known as Bernoulli's principle, which governs the design of wings. Flaps aid in the generation of lift as well as drag. Also, when taking off or landing, fly slowly without stalling. The tail is usually located in a remote portion of the plane. Assist with the plane's stabilization. Engines assist in propelling or pushing the vehicle forward. For land landings, landing gear might be wheels or a float for water landings. The landing gear is usually retracted to reduce drag.

Aircraft have long been used in battle, as well as for cargo and passenger transportation. Italy used the first combat plane against the Ottoman Empire in 1911. Most countries now have fixed-wing aircraft in their defense plans. This can include airplanes that fire guns, missiles or drop bombs. These also make it easier to conduct surveillance on the ground.[4]

Because we're looking into military planes. I'm going to hunt for one of the best autonomous military planes that can be used for operations. It's the MQ-9 Reaper Drone, often known as the Predator, from General Atomics. It can fly autonomously and be controlled remotely for military missions. Control remotely piloted vehicles anytime possible.

MQ-9 is a first design UAV for high-altitude surveillance and long reach. It's also sometime refer as hunter-killer [1]. It's large and heavier aircraft. A typical MQ9 system consists of military flight crew , sensor operator and Mission intelligence coordinator. This one has a 500 percent payload

Fig. 1. MQ9-Reaper Drone

increase and 9 times the horsepower. It has a full-tolerant flight system and meets or exceeds the reliability standards for manned aircraft. It can be configured to meet the mission's requirements. As previously stated, MQ9 has the following characteristics. below[7] :

Wing Span:	20m
Length	11m
Powerplant:	Honeywell TPE331-10
Max Gross Takeoff Weight:	4763 kg
Fuel Capacity:	1769 kg
Payload Capacity:	386 kg int and 1361 kg ext
Power:	11.0 kW/45.0 kVA
Performance :	
Max Altitude:	50,000 ft
Max Endurance:	27 hr
Max Air Speed:	240 KTAS

Since then, we've gained a good understanding of the vehicle, which is the main plot on which we'll develop an autopilot system for vehicle dynamics and control. The report will begin with the theoretical information that will be used in the development of this autopilot. The nonlinear model of airplane dynamics is more precise than the plane's linearized state space model. Between the longitudinal and lateral dynamics of the airplane, testing the controllers with the nonlinear model will get both the "longitudinal lateral" controllers in action at the same time, controlling the four control actions aileron, rudder, elevator, and thrust to maintain the required attitude altitude of the airplane while performing "coordinated-level turns" and "climb/descent." Then there's a quick overview of each component used to control this. The results and performance or behaviour of vehicle in the end. At end discuss and concluded upon the results.

II. Control

1) Rigid Body Equation of Motion: The rigid body equations of motion are derived from Newton's second law, which states that the summation of forces and moments acting on the aircraft is equal to the rate of change in linear momentum and angular momentums respectively.

$$\Sigma F = \frac{d(mV)}{dt} \tag{1}$$

$$\Sigma M = \frac{d(H)}{dt} \tag{2}$$

The above vector equations can be expressed by six scalar equations as follows:

$$\Sigma F_x = \frac{d}{dt}(mu), \Sigma F_y = \frac{d}{dt}(mv), \Sigma F_z = \frac{d}{dt}(mw), \tag{3}$$

$$L = \frac{d}{dt}H_x, M = \frac{d}{dt}H_y, N = \frac{d}{dt}H_z, \tag{4}$$

However, the motion of the aircraft cannot be fully defined by the body axes and hence fixed frame of reference was defined as : The flight absolute velocities are found in terms

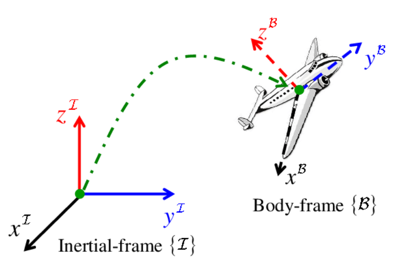

Fig. 2. Relation b/w body and inertial axis

of the Euler angles ψ , ϕ and θ components in the body frame as follows:

The angular velocities in the body frame are expressed in terms Euler rates are :

$$\begin{bmatrix} p \\ q \\ r \end{bmatrix} = \begin{bmatrix} 1 & 0 & -S_\theta \\ 0 & C_\phi & C_\theta S_\phi \\ 0 & -S_\phi & C_\theta C_\phi \end{bmatrix} \begin{bmatrix} \dot{\phi} \\ \dot{\theta} \\ \dot{\psi} \end{bmatrix}$$

While deriving the above equations, the aircraft is assumed as a rigid body with fixed mass acting on the aircraft center of mass.

$$\begin{bmatrix} \frac{dx}{dt} \\ \frac{dy}{dt} \\ \frac{dz}{dt} \end{bmatrix} = \begin{bmatrix} C_\theta C_\psi & S_\phi S_\theta C_\psi - C_\phi S_\psi & C_\phi S_\theta C_\psi + S_\phi S_\psi \\ C_\theta S_\psi & S_\phi S_\theta S_\psi + C_\phi C_\psi & C_\phi S_\theta S_\psi - S_\phi C_\psi \\ -S_\theta & S_\phi C_\theta & C_\phi C_\theta \end{bmatrix} \begin{bmatrix} u \\ v \\ w \end{bmatrix}$$

A. Fixed Wing Airplane Equations of Motion

The gravitational force components acting along the body of a fixed-wing aircraft are a function of the aircraft's orientation in space. The gravitational force will only contribute to the external forces because the body axes are fixed to the center of gravity. The components of gravitational force are as follows:

$$F_{x(}gravity) = -mgsin(\theta) \tag{5}$$

$$F_{y(}gravity) = mgcos(\theta)sin(\phi) \tag{6}$$

$$F_{z(}gravity) = -mgsin(\theta)cos(\phi) \tag{7}$$

Moreover, the propulsive thrust force can also have components that contribute to both the force along body axis and also moments if it doesn't act through the center of gravity.

B. Inertial or Earth axes and body axes

The axes that have no change in orientation or linear velocities throughout time are known as inertial axes (no linear accelerations). Body axes, on the other hand, are the axes attached to the airplane; their origin is the airplane's center of gravity, and they have the same linear and angular accelerations as the airplane itself as compared to the earth axes.

C. Forces and Moments

Calculate the Forces and Moments operating on an airplane as a result of the pilot's input signals, using the same airplane's stability and control derivatives at nominal flight conditions. The estimated Forces and Moments will be fed into the Rigid Body Dynamics (RBD) to create a complete non-linear flight simulator for an airplane.

1) Body Axes: As defined before, body axes are orthogonal axes which have their origin attached to the aircraft center of gravity and the x-z plane lies on the aircraft plane of symmetry. With this definition we can have infinite number of different systems of aircraft's body frames, each rotated about the y-axis by a certain angle ϵ There are 3 types of main body axes are : a) Stability axes : These are the axes where the X-axis lies on the total velocity component vector. In this case the normal and parallel forces are the lift and drag respectively. b)Body axes: These are the axes where the X-axis lies on the fuselage reference line.The angle between this frame and the stability body frame is the angle of attack at reference conditions. c) Principal Body axes: These axes coincide with the principal inertia axes the aircraft derivatives are different from one body frame to another as the aircraft moments of inertia. the derivatives and moment of inertia used to establish the nonlinear simulator model are the body axes.

2) Calculation: In order to calculate the aerodynamic forces and moments acting on the airplane by first identifying the factors affecting them as following :

$$\bar{f}_{Aerdyn,thr.} = f(\delta_a, \delta_r, \delta_e, \delta_T, u, v, w, p, q, r, \dot{u}, \dot{v}, \dot{w}, \dot{p}, \dot{q}, \dot{r}) \tag{8}$$

Following equations for the change of forces and moments can be put in matrix from as : The equations are then

$$\begin{bmatrix} \Delta X \\ \Delta Y \\ \Delta Z \\ \Delta L \\ \Delta M \\ \Delta N \end{bmatrix} = \begin{bmatrix} X_u & 0 & X_w & 0 & 0 & 0 & 0 & 0 & X_{\delta_e} & 0 & X_{\delta_T} \\ 0 & Y_v & 0 & Y_p & 0 & Y_r & 0 & 0 & 0 & Y_{\delta_r} & 0 \\ Z_u & 0 & Z_w & 0 & Z_q & 0 & Z_{\dot{w}} & 0 & Z_{\delta_e} & 0 & Z_{\delta_T} \\ 0 & L_v & 0 & L_p & 0 & L_r & 0 & L_{\delta_a} & 0 & L_{\delta_r} & 0 \\ M_u & 0 & M_w & 0 & M_q & 0 & M_{\dot{w}} & 0 & M_{\delta_e} & 0 & M_{\delta_T} \\ 0 & N_v & 0 & N_p & 0 & N_r & 0 & N_{\delta_a} & 0 & N_{\delta_r} & 0 \end{bmatrix} \begin{bmatrix} \Delta u \\ \Delta v \\ \Delta w \\ \Delta p \\ \Delta q \\ \Delta r \\ \Delta \dot{w} \\ \Delta \delta_a \\ \Delta \delta_e \\ \Delta \delta_r \\ \Delta \delta_T \end{bmatrix}$$

generated in MATLAB using simulink, using the derivatives of the airplane that has to be simulated along with the initial Forces and Moments, to get the Forces and Moments acting on the airplane at each time step. Before submitting the force values to the RBD solver, the gravitational force must be added to the forces calculated in the following way: The total force acting on an airplane in known to be given by:

$$X - mgsin_{\theta} = m(\dot{u} + qw - rv) \tag{9}$$

$$Y + mgcos_{\theta}sin\phi = m(\dot{v} + ru - pw) \tag{10}$$

$$Z + mgcos_{\theta}cos\phi = m(\dot{w} + pv - qu) \tag{11}$$

Airplane is in an equilibrium state:

$$X_0 = mgsin\theta_0 \tag{12}$$

$$Y_0 = -mgcos\theta_0 sin\phi_0 \tag{13}$$

$$Z_0 = -mgcos\theta_0 cos\phi_0 \tag{14}$$

$$X = \Delta(X) + mgsin\theta_0 \tag{15}$$

$$Y = \Delta(Y) - mgcos\theta_0 sin\phi_0 \tag{16}$$

$$Z = \Delta(Z) - mgcos\theta_0 cos\phi_0 \tag{17}$$

finally the total forces acting on the airplane are:

$$F_x = \Delta(X) + mgsin\theta_0 - mgsin\theta \tag{18}$$

$$F_y = \Delta(Y) - mgcos\theta_0 sin\phi_0 + mgcos\theta sin\phi \tag{19}$$

$$F_z = \Delta(Z) - mgcos\theta_0 cos\phi_0 + mgcos\theta cos\phi \tag{20}$$

These total forces together with the moments at each time step is to be given to the RBD solver in order to calculate the states of the airplane at each time step.

3) Equation of motion Linearization: The linear model is to be built by first linearizing the airplane equations of motion and write the state space matrix then use it obtain the linear state.The complete set of equations of motion of fixed wing airplane at a symmetric flight reference condition at which the angle of attack is not equal to zero are to be linearized. Then the equations of longitudinal and lateral dynamics are being decoupled and written in the state space form. After this step of linearization finally then built autopilot design for longitudinal and lateral control.

III. System Autopilot Design

Design the two major component for doing the Autopilot control i.e Longitudinal Autopilot control and Lateral Autopilot control. Below gonna explain in briefs these Autopilot control and their subpart.

A. Longitudinal Autopilot Design

The longitudinal autopilot is responsible of maintaining the desired aircraft speed, climb angle and hence altitude by output the required elevator and thrust control actions [5]. The linearized system representing the aircraft motion was modeled using the successive loop closure method. The loop configuration of the used control architecture for level flight condition.

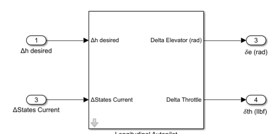

Fig. 3. Longitudinal Block

The longitudinal controller by breaking it into three control loops; elevator from pitch which is an inner loop that outputs the elevator command based on the pitch angle error. Meanwhile the outer loop -pitch from altitude- calculates the required pitch angle based on the error between the current and desired altitude. The third loop maintains the flight airspeed using throttle.

1) Pitch Controller: PID controller configuration was chosen and various iterations were done using matlab tool in order to reach the least possible settling time with acceptable results.

2) Velocity control: Used to compute the climb angle and altitude rate using the following equations.

$$\gamma = \theta - \alpha, where \alpha = V sin(\gamma) \tag{21}$$

It was expected that given a positive pitch command, the aircraft will climb upwards. However, the aircraft climbs for a while and then starts to dive downwards as the climb angle changes from positive to negative. This happens because increasing the pitch angle decreases the forward velocity until it reaches the stall value which is the inflection point resulting in loss of altitude[6]. Hence, a velocity controller should be designed to keep the aircraft trimmed by preserving the velocity.

3) Altitude Controller: In order to design the outer loop that holds the aircraft altitude, the transfer function relating the altitude to pitch angle can be obtained as follows:

$$\frac{h}{\theta} = -\frac{U_o}{s}\left(\frac{\alpha/\delta_e}{\theta/\delta_e} - 1\right) \tag{22}$$

The engine dynamics enforces the following limits on the thrust control action.δ_e

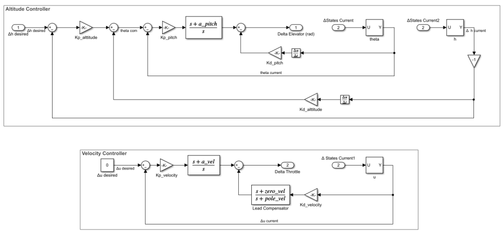

Fig. 4. Full Longitudinal Simulink Block

B. Lateral Autopilot Design

To achieve equilibrium flight condition when maneuvering in the lateral plane, a steady coordinated turn must be performed. A steady coordinated level turn means that the aircraft is kept at a constant altitude-controlled by the longitudinal autopilot- with no side slip while turning[9]. This is achieved when one lift component balances the weight of the aircraft while the other component provides enough force to generate centripetal acceleration. It's realized by two

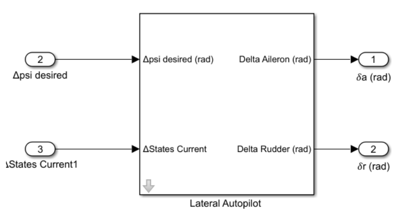

Fig. 5. Full Longitudinal Simulink Block

control surfaces; the ailerons are used to control the direction of lift vector while the rudder coordinates the maneuver to eliminate side slip. Controlling those two surfaces to achieve the required balance is the role of the lateral autopilot which will be designed in this section.

1) Yaw Damper: The yaw damper solves the problem of Dutch roll mode damping, it creates another problem when another flight mode requires a steady yaw rate that is not equal to zero (as it will control the rudder input to cancel out the motion) [12]. The solution for this problem is to use a washout circuit in the system controller to act as a high pass filter that eliminates the low frequency signal (steady state value of r) and only feeds back the high frequency signal to the controller.

2) Roll Controller: In order to design the roll controller to reach a desired bank angle, first, a new lateral state space model after adding the yaw damper to the system was got. The requirement of this controller is not to exceed maximum aileron deflection, which is the sum of the two aileron deflections is ± 50°, at the maximum bank angle (±30°)[11]. According to the above, by using matlab tool, PD controller configuration was chosen and various iterations on its gains was done to achieve a good response for unit step input within the limits of the aileron control action.

3) Coordination Turn: coordination requires zero lateral acceleration (β= 0) . Using the following, the required bank angle can be obtained for a given speed and turning rate. The tangential velocity :

$$u_0 = R\dot{\psi} \tag{23}$$

Summation of forces in the body y-axis gives:

$$tan\phi = \phi = \frac{u_0\psi}{g} \tag{24}$$

Where the turning rate is obtained as :

$$\dot{\psi} = \frac{1}{\tau_1}(\psi_d - \psi) \tag{25}$$

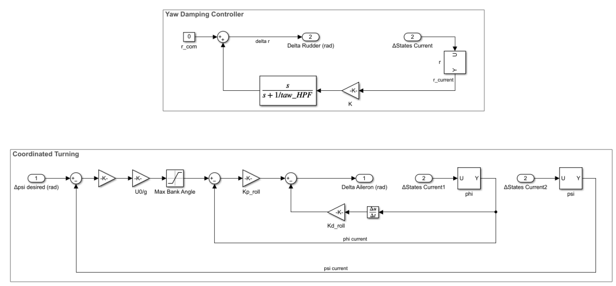

Fig. 6. Full Lateral Block

C. Autopilot system

After building the non-linear simulator on Simulink[10] , build this model to verify the autopilot system by taking the output control actions from the autopilot and calculate the states using the non-linear model.

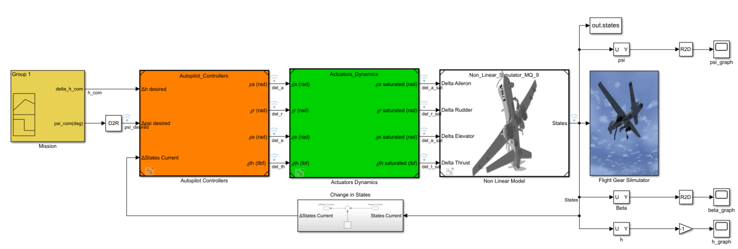

Fig. 7. Full Model of an Autopilot for MQ9

IV. Model Setup

To evaluate the proposed method and testing was done in a simulator world where some course was given to MQ9-reaper drone to follow an trajectory and do some require action for completing the whole mission. In this section we'll be looking into how to setup an plane model for 3D visualization and also communicating with the commands sends for the Simulink.

A. Flightgear

Flightgear is a free open source program that is frequently used for research purposes in the aerospace industry. It aids in the simulation of a variety of environmental parameters, including input and output to the system. Can also model various surface features. Set up environmental conditions based on windflow and other factors. It also supports numerous flight dynamics engines with help from other sources, such as Matlab/Simulink in this case. It's often used in industry for simulation. [8]

Fig. 8. Flightgear

1) Setting Up Mq9 Flightgear: For setting up and installing aircraft there are two option. 1) Go through the aircraft tab. Click on Browse and select an aircraft model needed then install it. After installing just select it. There you go with an 3D model of your aircraft[2].
2)If couldn't find in aircraft tab then go to Flightgear.org search for aircraft model. Download a zip and upload it to the Home directory of the Flightgear in local drive. Then you can see that model in flight-gear on starting it up.

2) Flightgear+Simulink: Simulink already has an flightgear preconfigure 6DOF block for animation.

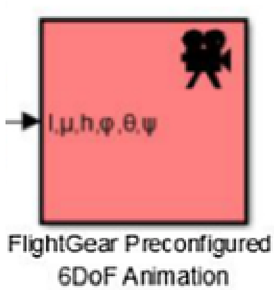

Fig. 9. Flightgear simulink block

It's configure as a sim viewing device. Simulink can obtain data and transmit it further pos and attitude to flightgear.

V. Results

In this we now join everything our simulink model and flightgear to do the desire and have the output of the behaviour of model.

A. Experiment

Finally, we integrate the whole autopilot system together and test it with the non-linear model by making certain task which consists of:

- Climb to altitude of 10,000 ft at 1500 ft/min rate
- Cruise at constant velocity and heading angle for 2 minutes
- Make a circle by commanding a change in the heading angle with 360°
- Cruise at constant velocity and heading angle for 2 minutes
- Climbing turn by commanding a change in the heading angle with 30° along with a step input of 100 ft in altitude
- Descend down to the initial altitude by reducing the altitude by 10,000 ft at 1500 ft/min decent rate

Results of above mission ::

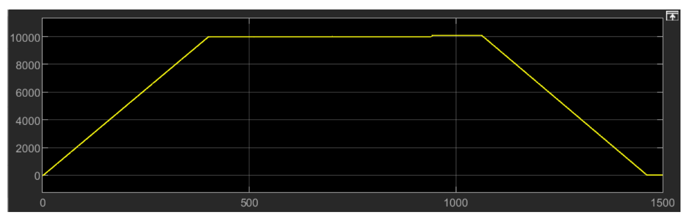

Fig. 10. Altitude profile

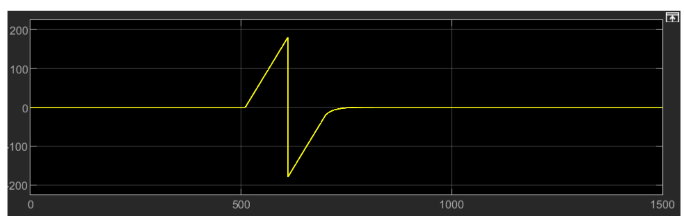

Fig. 11. Yaw Profile

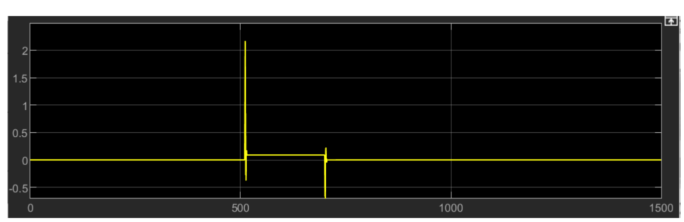

Fig. 12. Side Slip angle

VI. Conclusion

The paper describes implementation of the Fixed wing MQ9-reaper drone. To achieve it's goal designed a mission for MQ9 to climb do a roll and descend. Author was able to achieve this task using Simulink. The two main controller introduce were longitudinal and lateral for flight dynamics control. Although there were some jerks were seen because of smoothness constraints. When doing a roll while rotating 360 some small deviation. Future work instead of using a Flightgear simulator can introduce a VR to actually able to see the plane in one's environment. Also add adaptive machine learning to keep improving based on controls too.

Video URL: https://www.youtube.com/watch?v=aGMJ5hAYYmk

GitHub URL: https://github.com/r0b0shubham96/GNC$MQ9SDU$

References

[1] Courtney Albon. General atomics pitching future reaper upgrades: Air force phasing out mq-1 sustainment, strengthening mq-9 fleet. *Inside the Air Force*, 24(51):1–9, 2013.

[2] Michael Basler, Martin Spott, Stuart Buchanan, Jon Berndt, Bernhard Buckel, Cameron Moore, Curt Olson, Dave Perry, Michael Selig, Darrell Walisser, et al. The flightgear manual. *The FlightGear Manual*, 2010.

[3] Vladimír BEŇO and František ADAMČÍK Jr. Unmanned combat air vehicle: Mq-9 reaper. *Scientific Research & Education in the Air Force-AFASES*, 1, 2014.

[4] Roman Czyba, Marcin Lemanowicz, Zbigniew Gorol, and Tomasz Kudala. Construction prototyping, flight dynamics modeling, and aerodynamic analysis of hybrid vtol unmanned aircraft. *Journal of Advanced Transportation*, 2018, 2018.

[5] Derrick Downing and Stephen Ganley. Micropilot autopilot. 2015.

[6] Özgür Dündar, Mesut Bilici, and Tarık Ünler. Design and performance analyses of a fixed wing battery vtol uav. *Engineering Science and Technology, an International Journal*, 23(5):1182–1193, 2020.

[7] John Hamilton. *UAVs: Unmanned aerial vehicles*. ABDO Publishing Company, 2012.

[8] Alexander R Perry. The flightgear flight simulator. In *Proceedings of the USENIX Annual Technical Conference*, volume 686, 2004.

[9] A Prach. A lateral autopilot for a tactical uav. 2009.

[10] MO Rauw. Fdc 1.2-a simulink toolbox for flight dynamics and control analysis. *Haarlem, The Netherlands*, pages 26–39, 2001.

[11] Wei Ren. Trajectory tracking control for a miniature fixed-wing unmanned air vehicle. *International journal of systems science*, 38(4):361–368, 2007.

[12] Jan Roskam. *Airplane flight dynamics and automatic flight controls*. DARcorporation, 1995.